

Puzzles in charm spectroscopy

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We briefly analyze aspects of open and hidden charm resonances, discussing in particular the mesons $D_{sJ}(2860)$ and $X(3872)$.

§1. Prologue

The word *puzzle* means a *problem*, a mystery deserving explanation. It also indicates a *game designed for testing ingenuity*, where pieces of information have to be put together to reassemble a known picture. It is worth asking if recent results in charm spectroscopy¹⁾ represent problems or information fitting into a known theoretical scheme. The answer is different in case of open and hidden charm mesons.

§2. $c\bar{s}$ system and $D_{sJ}(2860)$

An example of new experimental information fitting into an established theoretical scheme is the meson $D_{sJ}(2860)$ recently observed by BaBar Collaboration²⁾ in the DK system inclusively produced in $e^+e^- \rightarrow DKX$, with $M(D_{sJ}(2860)) = 2856.6 \pm 1.5 \pm 5.0$ MeV and $\Gamma(D_{sJ}(2860) \rightarrow DK) = 47 \pm 7 \pm 10$ MeV ($DK = D^0K^+ + D^+K_S^0$). Together with this state, a broad structure was noticed with $M = 2688 \pm 4 \pm 3$ MeV and $\Gamma = 112 \pm 7 \pm 36$ MeV; indeed, Belle Collaboration³⁾ reported the evidence of $D_{sJ}(2715)$ in $B^+ \rightarrow \bar{D}^0 D^0 K^+$ decays, with $M(D_{sJ}(2715)) = 2715 \pm 11^{+11}_{-14}$ MeV, $\Gamma(D_{sJ}(2715)) = 115 \pm 20^{+36}_{-32}$ MeV and $J^P = 1^-$.

The interpretation of these charmed resonances is easier in the heavy quark limit $m_Q \rightarrow \infty$. In such a limit the spin s_Q of the heavy quark and the angular momentum s_ℓ of the meson light degrees of freedom: $s_\ell = s_{\bar{q}} + \ell$ ($s_{\bar{q}}$ light antiquark spin, ℓ orbital angular momentum of the light degrees of freedom relative to the heavy quark) are decoupled, and the spin-parity s_ℓ^P is conserved in strong interaction processes.⁵⁾ Mesons can be classified as doublets of s_ℓ^P . Two states (P, P^*) with $J^P = (0^-, 1^-)$ correspond to $\ell = 0$. The four states corresponding to $\ell = 1$ can be collected in two doublets, one (P_0^*, P_1') with $s_\ell^P = \frac{1}{2}^+$ and $J^P = (0^+, 1^+)$, another one (P_1, P_2) with $s_\ell^P = \frac{3}{2}^+$ and $J^P = (1^+, 2^+)$. For $\ell = 2$ the doublets have $s_\ell^P = \frac{3}{2}^-$ ($(P_1^{*'}, P_2^*)$ with $J^P = (1^-, 2^-)$) and $s_\ell^P = \frac{5}{2}^-$ ($(P_2^{*'}, P_3)$ with $J^P = (2^-, 3^-)$).

In case of charm, m_c is greater than the strong interaction scale Λ_{QCD} but it is not very large; therefore, corrections can be expected compared to the infinite limit. $O(\frac{1}{m_c})$ effects are the hyperfine splitting between mesons belonging to the same s_ℓ^P doublet, and the mixing of states with same J^P and different s_ℓ^P , namely the two

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axial vector states with $s_\ell^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$.

The six $c\bar{s}$ states reported by PDG 2006⁴⁾ can be classified according to this scheme. D_s and D_s^* belong to the $s_\ell^P = \frac{1}{2}^-$ doublet. There are four candidates for the four $\ell = 1$ states: $D_{sJ}^*(2317)$ ($J^P = 0^+$), $D_{sJ}(2460)$ and $D_{s1}(2536)$ ($J^P = 1^+$), and $D_{s2}(2573)$ ($J^P = 2^+$). The natural assignment is $D_{sJ}^*(2317)$ to the $s_\ell^P = \frac{1}{2}^+$ doublet and $D_{s2}(2573)$ to the $s_\ell^P = \frac{3}{2}^+$ doublet. As for $D_{sJ}(2460)$ and $D_{s1}(2536)$, they can be a mixing of the 1^+ $s_\ell^P = \frac{1}{2}^+$ and $\frac{3}{2}^+$ $c\bar{s}$ states. However, in case of non strange axial-vector $c\bar{q}$ mesons the measured mixing angle is small,⁶⁾ a result confirmed by an analysis of $O(\frac{1}{m_c})$ effects breaking the heavy quark spin symmetry.⁷⁾ Invoking $SU(3)_F$, also the mixing angle in the case of $c\bar{s}$ is expected to be small, so that $D_{s1}(2536)$ and $D_{sJ}(2460)$ essentially coincide with the $s_\ell^P = \frac{3}{2}^+$ and $\frac{1}{2}^+$ states.

In the above classification $D_{sJ}(2860)$, which decays in two pseudoscalar mesons, can be either a $J^P = 1^-$ $s_\ell^P = \frac{3}{2}^-$ state, or a $J^P = 3^-$ $s_\ell^P = \frac{5}{2}^-$ state, i.e. a state with $\ell = 2$ and lowest radial quantum number. Another possibility is that $D_{sJ}(2860)$ is a radial excitation of the $J^P = 1^-$ $s_\ell^P = \frac{1}{2}^-$ state (D_s^*), of the $J^P = 0^+$ $s_\ell^P = \frac{1}{2}^+$ state (first radial excitation of $D_{sJ}^*(2317)$) or of the $J^P = 2^+$ $s_\ell^P = \frac{3}{2}^+$ state (D_{s2}'). The J^P assignment can be done considering the decay modes and width.

It was suggested⁸⁾ that a few high mass and high spin charm states could be narrow enough to be observed and, in particular, that the 3^- state belonging to the $s_\ell^P = \frac{5}{2}^-$ $c\bar{q}$ ($c\bar{s}$) doublet is not too broad since it decays to $D\pi$ (DK) in f -wave. An analysis⁹⁾ based on the heavy quark limit¹⁰⁾ supports the assignment. We define the fields representing the various heavy-light meson doublets: H_a for $s_\ell^P = \frac{1}{2}^-$ (a light flavour index), S_a and T_a for $s_\ell^P = \frac{1}{2}^+$ and $s_\ell^P = \frac{3}{2}^+$, respectively, and X_a and X_a' for the doublets corresponding to $\ell = 2$, $s_\ell^P = \frac{3}{2}^-$ and $s_\ell^P = \frac{5}{2}^-$, respectively:

$$\begin{aligned}
H_a &= \frac{1+\not{v}}{2} [P_{a\mu}^* \gamma^\mu - P_a \gamma_5] \quad , \quad S_a = \frac{1+\not{v}}{2} [P_{1a}^{\prime\mu} \gamma_\mu \gamma_5 - P_{0a}^*] \quad , \\
T_a^\mu &= \frac{1+\not{v}}{2} \left\{ P_{2a}^{\mu\nu} \gamma_\nu - P_{1a\nu} \sqrt{\frac{3}{2}} \gamma_5 \left[g^{\mu\nu} - \frac{1}{3} \gamma^\nu (\gamma^\mu - v^\mu) \right] \right\} \quad , \\
X_a^\mu &= \frac{1+\not{v}}{2} \left\{ P_{2a}^{*\mu\nu} \gamma_5 \gamma_\nu - P_{1a\nu}^{*'} \sqrt{\frac{3}{2}} \left[g^{\mu\nu} - \frac{1}{3} \gamma^\nu (\gamma^\mu - v^\mu) \right] \right\} \quad , \\
X_a^{\prime\mu\nu} &= \frac{1+\not{v}}{2} \left\{ P_{3a}^{\mu\nu\sigma} \gamma_\sigma - P_{2a}^{*\prime\alpha\beta} \sqrt{\frac{5}{3}} \gamma_5 \left[g_\alpha^\mu g_\beta^\nu - \frac{1}{5} \gamma_\alpha g_\beta^\nu (\gamma^\mu - v^\mu) - \frac{1}{5} \gamma_\beta g_\alpha^\mu (\gamma^\nu - v^\nu) \right] \right\}
\end{aligned} \tag{2.1}$$

with the various operators annihilating mesons of four-velocity v . The interaction of these particles with the octet of light pseudoscalar mesons, introduced using $\xi = e^{\frac{i\mathcal{M}}{f_\pi}}$, $\Sigma = \xi^2$, the matrix \mathcal{M} containing the octet of π, K and η fields, and $f_\pi = 132$ MeV, is described by an effective Lagrangian invariant under chiral and heavy-quark spin-flavour transformations. At the leading order in the $1/m_Q$ and light meson momentum expansion, the decays $F \rightarrow HM$ ($F = H, S, T, X, X'$ and M a light

pseudoscalar meson) are described by the Lagrangian terms:¹¹⁾

$$\begin{aligned}
\mathcal{L}_H &= g \text{Tr}[\bar{H}_a H_b \gamma_\mu \gamma_5 \mathcal{A}_{ba}^\mu] \\
\mathcal{L}_S &= h \text{Tr}[\bar{H}_a S_b \gamma_\mu \gamma_5 \mathcal{A}_{ba}^\mu] + h.c., \\
\mathcal{L}_T &= \frac{h'}{\Lambda_\chi} \text{Tr}[\bar{H}_a T_b^\mu (i D_\mu \mathcal{A} + i \mathcal{D} \mathcal{A}_\mu)_{ba} \gamma_5] + h.c. \\
\mathcal{L}_X &= \frac{k'}{\Lambda_\chi} \text{Tr}[\bar{H}_a X_b^\mu (i D_\mu \mathcal{A} + i \mathcal{D} \mathcal{A}_\mu)_{ba} \gamma_5] + h.c. \\
\mathcal{L}_{X'} &= \frac{1}{\Lambda_\chi^2} \text{Tr}[\bar{H}_a X_b'^{\mu\nu} [k_1 \{D_\mu, D_\nu\} \mathcal{A}_\lambda + k_2 (D_\mu D_\nu \mathcal{A}_\lambda + D_\nu D_\lambda \mathcal{A}_\mu)]_{ba} \gamma^\lambda \gamma_5] + h.c.
\end{aligned} \tag{2.2}$$

where Λ_χ is the chiral symmetry-breaking scale ($\Lambda_\chi = 1 \text{ GeV}$), $D_{\mu ba} = -\delta_{ba} \partial_\mu + \frac{1}{2} (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)_{ba}$ and $\mathcal{A}_{\mu ba} = \frac{i}{2} (\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)_{ba}$. \mathcal{L}_S and \mathcal{L}_T describe transitions of positive parity heavy mesons with the emission of light pseudoscalar mesons in s - and d - wave, respectively, with g, h and h' effective coupling constants. \mathcal{L}_X and $\mathcal{L}_{X'}$ describe the transitions of higher mass mesons of negative parity with the emission of light pseudoscalar mesons in p - and f - wave with couplings k', k_1 and k_2 .

At the same order in the expansion in the light meson momentum, the structure of the Lagrangian terms for radial excitations of H , S and T doublets does not change, but the coupling constants g, h and h' are substituted by \tilde{g}, \tilde{h} and \tilde{h}' .

In Table I we collect the ratios $\frac{\Gamma(D_{sJ}(2860) \rightarrow D^* K)}{\Gamma(D_{sJ}(2860) \rightarrow DK)}$ and $\frac{\Gamma(D_{sJ}(2860) \rightarrow D_s \eta)}{\Gamma(D_{sJ}(2860) \rightarrow DK)}$ obtained for various quantum number assignments to $D_{sJ}(2860)$.⁹⁾ These ratios can

Table I. Predicted ratios $\frac{\Gamma(D_{sJ} \rightarrow D^* K)}{\Gamma(D_{sJ} \rightarrow DK)}$ and $\frac{\Gamma(D_{sJ} \rightarrow D_s \eta)}{\Gamma(D_{sJ} \rightarrow DK)}$ (with $DK = D^0 K^+ + D^+ K_S^0$) for various assignment of quantum numbers to $D_{sJ}(2860)$.

$D_{sJ}(2860)$	$D_{sJ}(2860) \rightarrow DK$	$\frac{\Gamma(D_{sJ} \rightarrow D^* K)}{\Gamma(D_{sJ} \rightarrow DK)}$	$\frac{\Gamma(D_{sJ} \rightarrow D_s \eta)}{\Gamma(D_{sJ} \rightarrow DK)}$
$s_\ell^p = \frac{1}{2}^-, J^P = 1^-, \text{rad. excit.}$	$p\text{-wave}$	1.23	0.27
$s_\ell^p = \frac{1}{2}^+, J^P = 0^+, \quad "$	$s\text{-wave}$	0	0.34
$s_\ell^p = \frac{3}{2}^+, J^P = 2^+, \quad "$	$d\text{-wave}$	0.63	0.19
$s_\ell^p = \frac{3}{2}^-, J^P = 1^-$	$p\text{-wave}$	0.06	0.23
$s_\ell^p = \frac{5}{2}^-, J^P = 3^-$	$f\text{-wave}$	0.39	0.13

be used to exclude some assignments. Indeed, since a $D^* K$ signal has not been observed (so far) in the $D_{sJ}(2860)$ mass range, the production of $D^* K$ is not favoured and therefore $D_{sJ}(2860)$ is not a radial excitation of D_s^* or D_{s2} . The assignment $s_\ell^p = \frac{3}{2}^-, J^P = 1^-$ can also be excluded: the width $\Gamma(D_{sJ}(2860) \rightarrow DK)$ obtained using (2.2) would be $\Gamma(D_{sJ}(2860) \rightarrow DK) \geq 1 \text{ GeV}$ using $k' \simeq h' \simeq 0.45 \pm 0.05$,⁷⁾ and there is no reason to presume that the coupling constant k' is sensibly smaller.

In the case of the assignment $s_\ell^p = \frac{1}{2}^+, J^P = 0^+$, proposed in some analyses,¹²⁾ the decay $D_{sJ}(2860) \rightarrow D^* K$ is forbidden and the transition into DK occurs in s -wave. The coupling constant for the lowest radial quantum number was computed: $h \simeq -0.55$;¹³⁾ using this value for \tilde{h} we would obtain $\Gamma(D_{sJ}(2860) \rightarrow DK) \geq 1 \text{ GeV}$.

It is reasonable to suppose that $|\tilde{h}| < |h|$, although no information is available about couplings of radially excited heavy-light mesons to low-lying states: the experimental width corresponds to $\tilde{h} = 0.1$. A large signal in the $D_s\eta$ channel would be expected. A problem is that, if $D_{sJ}(2860)$ is a 0^+ radial excitation, its partner with $J^P = 1^+$ would decay to D^*K with a width of the order of 40 MeV. Since both the lowest lying states with $J^P = 0^+$ and 1^+ , $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$, are produced in charm continuum at B factories, to explain the absence of the D^*K signal at energy around 2860 MeV one must invoke a mechanism favouring the production of the 0^+ first radial excitation and inhibiting the production of the 1^+ radial excitation.

In the last case $s_\ell^P = \frac{5}{2}^-$, $J^P = 3^-$ the narrow DK width is due to the kaon momentum suppression: $\Gamma(D_{sJ}(2860) \rightarrow DK) \propto q_K^7$. A smaller but non negligible signal in the D^*K mode is predicted, and a small signal in the $D_s\eta$ mode is also expected. The state of spin two $D_{s2}^{*'}$ belonging to the $s_\ell^P = \frac{5}{2}^-$ doublet, which can decay to D^*K and not to DK , would be narrow: $\Gamma(D_{s2}^{*'} \rightarrow D^*K) \simeq 50$ MeV for $m_Q \rightarrow \infty$: as an effect of $1/m_Q$ corrections, $D_{s2}^{*'} \rightarrow D^*K$ can occur in p -wave, in which case $\Gamma(D_{s2}^{*'})$ could be broader.

$D_{sJ}(2860)$ with $J^P = 3^-$ is not expected to be produced in non leptonic B decays such as $B^0 \rightarrow D^- D_{sJ}(2860)^+$ and $B^+ \rightarrow \bar{D}^0 D_{sJ}(2860)^+$: indeed in the Dalitz plot analysis of $B^+ \rightarrow \bar{D}^0 D^0 K^+$ Belle found no signal of $D_{sJ}(2860)$.³⁾ The non-strange partner D_3 of a $J^P = 3^-$ $D_{sJ}(2860)$ state, if the mass splitting $M_{D_{sJ}(2860)} - M_{D_3}$ is of the order of the strange quark mass, is also expected to be narrow: $\Gamma(D_3^+ \rightarrow D^0 \pi^+) \simeq 37$ MeV. It can be produced in semileptonic as well as in non leptonic B decays, such as $B^0 \rightarrow D_3^- \ell^+ \bar{\nu}_\ell$ and $B^0 \rightarrow D_3^- \pi^+$.⁹⁾

The analysis of $D_{sJ}(2715)$ can be done analogously and is in progress. A proposal for the $c\bar{s}$ spectrum is shown in fig.1.

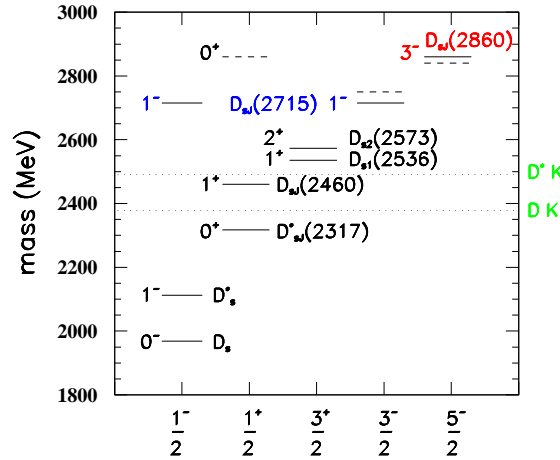


Fig. 1. $c\bar{s}$ spectrum with possible assignments of $D_{sJ}(2860)$ and $D_{sJ}(2715)$.

§3. Hidden charm mesons and $X(3872)$

A puzzle in the hidden charm sector is the meson $X(3872)$ discovered in the $J/\psi\pi^+\pi^-$ invariant mass distribution in B decays and in $p\bar{p}$ collisions,¹⁴⁾ with $M(X) = 3871.2 \pm 0.5$ MeV and $\Gamma(X) < 2.3$ MeV (90% C.L.).⁴⁾ The $\pi^+\pi^-$ spectrum is peaked for large invariant mass.¹⁵⁾ $X(3872)$ was not observed in e^+e^- annihilation and in $\gamma\gamma$ fusion; searches of charged partners also produced negative results. The charge conjugation of the state is $C=+1$ since the mode $X \rightarrow J/\psi\gamma$ was observed;¹⁶⁾ angular distribution studies show that the most likely quantum number assignment is $J^{PC} = 1^{++}$.¹⁷⁾

Furthermore, a near-threshold $D^0\bar{D}^0\pi^0$ enhancement in $B \rightarrow D^0\bar{D}^0\pi^0 K$ decay was recently reported, with the peak at $M = 3875.4 \pm 0.7_{-2.0}^{+1.2}$ MeV and $B(B \rightarrow KX \rightarrow KD^0\bar{D}^0\pi^0) = (1.27 \pm 0.31_{-0.39}^{+0.22}) \times 10^{-4}$.¹⁸⁾ If the enhancement is only due to $X(3872)$ one finds $\frac{B(X \rightarrow D^0\bar{D}^0\pi^0)}{B(X \rightarrow J/\psi\pi^+\pi^-)} = 9 \pm 4$, hence X mainly decays into final states with open charm mesons. Notice that the central value of the mass measured in $D^0\bar{D}^0\pi^0$ is 4 MeV higher than the PDG value (with a large systematic error).

Since another hadronic decay mode was observed for $X(3872)$: $X \rightarrow J/\psi\pi^+\pi^-\pi^0$ with $\frac{B(X \rightarrow J/\psi\pi^+\pi^-\pi^0)}{B(X \rightarrow J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$,^{16), 19)} there are G-parity violating X transitions or, if the two modes are considered as induced by ρ^0 and ω intermediate states, isospin violation: this suggested the conjecture that $X(3872)$ is not a charmonium $\bar{c}c$ state. In the search of the right interpretation, the coincidence between the X mass as averaged by PDG and the $D^{*0}\bar{D}^0$ mass: $M(D^{*0}\bar{D}^0) = 3871.2 \pm 1.0$ MeV, inspired the proposal that $X(3872)$ could be a realization of the molecular quarkonium,²⁰⁾ a D^{*0} and \bar{D}^0 bound state with small binding energy,²¹⁾ an interpretation that would allow to account for a few properties of $X(3872)$. For example, describing the wave function of $X(3872)$ through various hadronic components:²²⁾

$$|X(3872)\rangle = a|D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0\rangle + b|D^{*+}D^- + D^{*-}D^+\rangle + \dots \quad (3.1)$$

(with $|b| \ll |a|$) one could explain why this state seems not to have definite isospin, why the mode $X \rightarrow J/\psi\pi^0\pi^0$ was not found, and why, if the molecular binding mechanism is provided by a single pion exchange, there are no $D\bar{D}$ molecular states. It has also been suggested that the molecular interpretation implies that the radiative decay in neutral D mesons: $X \rightarrow D^0\bar{D}^0\gamma$ should be dominant with respect to $X \rightarrow D^+D^-\gamma$.²²⁾

The description of $X(3872)$ in a simple charmonium scheme, in which it would be identified as the first radial excitation of the $J^{PC} = 1^{++}$ state, presents alternative arguments to the molecular description.²³⁾ For example, the molecular binding mechanism has not been clearly identified.^{1), 24)} Concerning the large value of the ratio $\frac{B(X \rightarrow J/\psi\pi^+\pi^-\pi^0)}{B(X \rightarrow J/\psi\pi^+\pi^-)}$ one has to consider that phase space effects in two and three pion modes are very different. The ratio of the amplitudes is smaller: $\frac{A(X \rightarrow J/\psi\rho^0)}{A(X \rightarrow J/\psi\omega)} \simeq 0.2$, so that the isospin violating amplitude is 20% of the isospin conserving one, an effect that could be related to another isospin violating effect, the mass difference between neutral and charged D mesons, considering the contribution of DD^* inter-

mediate states to X decays. The prediction $\Gamma(B^0 \rightarrow XK^0) \simeq \Gamma(B^- \rightarrow XK^-)$, based on the charmonium description, is neither confirmed nor excluded, since $\frac{B(B^0 \rightarrow K^0 X)}{B(B^+ \rightarrow K^+ X)} = 0.50 \pm 0.30 \pm 0.05$.²⁵⁾ The $\bar{c}c$ interpretation leaves unsolved the issue of the eventual overpopulation of the level corresponding to the first radial excitations of 1^{++} $\bar{c}c$ states resulting from the possible assignment of these quantum numbers to another structure observed by Belle Collaboration, $Y(3930)$,¹⁹⁾ however, since this other resonance is still not confirmed and its properties not fully understood, the charmonium option for $X(3872)$ seems not excluded, yet. A warning comes from the $D^0 \bar{D}^0 \pi^0$ signal which can contribute to settle the question of the coincidence of the X and $D^0 \bar{D}^{*0}$ mass: an X mass above the $D^0 \bar{D}^{*0}$ threshold would be difficult to explain in the molecular scheme.²⁶⁾

The suggestion that observation of the dominance of $X \rightarrow D^0 \bar{D}^0 \gamma$ with respect to $X \rightarrow D^+ D^- \gamma$ can be interpreted as a signature of the molecular structure of $X(3872)$ ²²⁾ is also problematic.²⁷⁾ Assuming that $X(3872)$ is an ordinary $J^{PC} = 1^{++}$ charmonium state together with a standard mechanism for X radiative transition into charmed mesons, the ratio $R = \frac{\Gamma(X \rightarrow D^+ D^- \gamma)}{\Gamma(X \rightarrow D^0 \bar{D}^0 \gamma)}$ is small, and it is tiny in a wide range of the hadronic parameters governing the decays, therefore $R \ll 1$ is not peculiar of a molecular quarkonium $X(3872)$.²⁷⁾ This can be demonstrated describing the $X(3872) \rightarrow D \bar{D} \gamma$ amplitude by diagrams with intermediate particles nearest to their mass shell, as those depicted in fig.2 with D^* and $\psi(3770)$ as intermediate states. The amplitude can be expressed in terms of two unknown quantities: a coupling \hat{g}_1 governing the $X D D^*(D \bar{D}^*)$ matrix elements, and a coupling c appearing in the $X \psi(3770) \gamma$ matrix element, all the other quantities being fixed by experimental data.^{27), 28)} As shown in fig.3, the ratio R is tiny for small values of c/\hat{g}_1 ,

The photon spectrum is different in case of a charmonium or a molecule. It is interesting to consider it in X decays to neutral and charged D meson pairs for two representative values: $c/\hat{g}_1 = 1$ and 300 (fig.4). For low value of c/\hat{g}_1 , i.e. in the condition where the intermediate D^* dominates the decay amplitude, the photon spectrum in the $D^0 \bar{D}^0 \gamma$ mode coincides with the line corresponding to the D^* decay at $E_\gamma \simeq 139$ MeV. The narrow peak is different from the line shape expected in a molecular description, which is related to the wave function of the two heavy mesons bounded in the $X(3872)$, in particular to the binding energy of the system, being broader for larger binding energy. On the other hand, the photon spectrum in the charged $D^+ D^- \gamma$ mode is broader, with a peak at $E_\gamma \simeq 125$ MeV, the total $X \rightarrow D^+ D^- \gamma$ rate being severely suppressed with respect to $X \rightarrow D^0 \bar{D}^0 \gamma$.

At the opposite side of the c/\hat{g}_1 range, where $\psi(3770)$ gives a large contribution to the radiative amplitude, a peak at $E_\gamma \simeq 100$ MeV appears both in neutral and charged D meson modes, in the first case together with the structure at $E_\gamma \simeq 139$

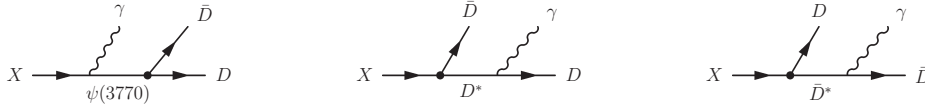


Fig. 2. Diagrams contributing to $X(3872) \rightarrow D \bar{D} \gamma$.

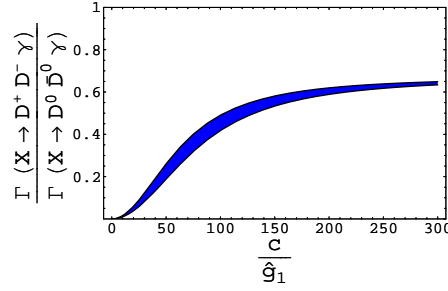


Fig. 3. Ratio of charged $X \rightarrow D^+D^-\gamma$ to neutral $X \rightarrow D^0\bar{D}^0\gamma$ decay widths versus c/\hat{g}_1 .

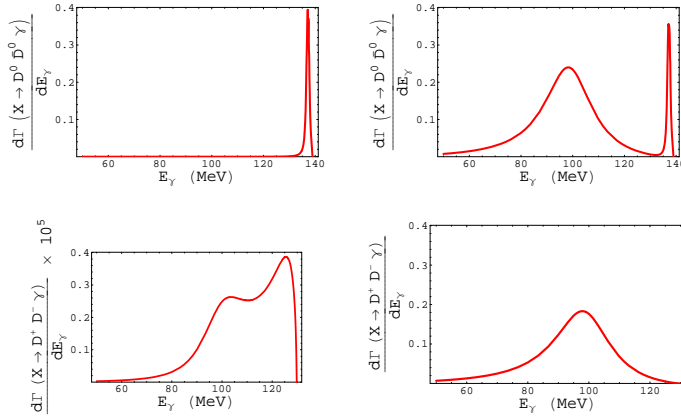


Fig. 4. Photon spectrum (in arbitrary units) in $X \rightarrow D^0\bar{D}^0\gamma$ (top) and $X \rightarrow D^+D^-\gamma$ (bottom) decays for values of the hadronic parameter $c/\hat{g}_1 = 1$ (left) and $c/\hat{g}_1 = 300$ (right).

MeV. This spectrum was previously described and the radiative decay was interpreted as due to the $\bar{c}c$ core of $X(3872)$.²²⁾ So, the measurement of the photon spectrum $\Gamma(X \rightarrow D\bar{D}\gamma)$ could be used to shed light on the structure of $X(3872)$.

§4. Conclusions

A few results in charm spectroscopy challenge our understanding. More than thirty years after the first observation, charm continues to be a surprise for us.

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References

- 1) For other reviews see: P. Colangelo, F. De Fazio and R. Ferrandes, *Mod. Phys. Lett. A* **19** (2004) 2083; E. S. Swanson, *Phys. Rept.* **429** (2006) 243; J. L. Rosner, arXiv:hep-ph/0609195; P. Colangelo, F. De Fazio, R. Ferrandes and S. Nicotri, arXiv:hep-ph/0609240; S. L. Zhu, arXiv:hep-ph/0703225.
- 2) B. Aubert [BABAR Collaboration], *Phys. Rev. Lett.* **97** (2006) 222001.
- 3) K. Abe *et al.*, [Belle Collaboration], arXiv:hep-ex/0608031.
- 4) W. M. Yao *et al.* [Particle Data Group], *J. Phys. G* **33** (2006) 1.
- 5) For review see: M. Neubert, *Phys. Rept.* **245** (1994) 259.
- 6) K. Abe *et al.* [Belle Collaboration], *Phys. Rev. D* **69** (2004) 112002.
- 7) P. Colangelo, F. De Fazio and R. Ferrandes, *Phys. Lett. B* **634** (2006) 235.
- 8) P. Colangelo, F. De Fazio and G. Nardulli, *Phys. Lett. B* **478** (2000) 408.
- 9) P. Colangelo, F. De Fazio and S. Nicotri, *Phys. Lett. B* **642** (2006) 48.
- 10) N. Isgur and M. B. Wise, *Phys. Rev. Lett.* **66** (1991) 1130; *Phys. Rev. D* **43** (1991) 819; U. Kilian, J. G. Körner and D. Pirjol, *Phys. Lett. B* **288** (1992) 360; A. F. Falk and M. Luke, *Phys. Lett. B* **292** (1992) 119.
- 11) M. B. Wise, *Phys. Rev. D* **45** (1992) R2188; G. Burdman and J. F. Donoghue, *Phys. Lett. B* **280** (1992) 287; P. Cho, *Phys. Lett. B* **285** (1992) 145; H.-Y. Cheng *et al.*, *Phys. Rev. D* **46** (1992) 1148; R. Casalbuoni *et al.*, *Phys. Lett. B* **299** (1993) 139.
- 12) E. van Beveren and G. Rupp, *Phys. Rev. Lett.* **97** (2006) 202001; F. E. Close, C. E. Thomas, O. Lakhina and E. S. Swanson, *Phys. Lett. B* **647** (2007) 159.
- 13) P. Colangelo *et al.*, *Phys. Rev. D* **52** (1995) 6422; P. Colangelo and F. De Fazio, *Eur. Phys. J. C* **4** (1998) 503 and *Phys. Lett. B* **570** (2003) 180.
- 14) S. K. Choi *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **91** (2003) 262001; B. Aubert *et al.* [BABAR Collaboration], *Phys. Rev. D* **71** (2005) 071103; D. Acosta *et al.* [CDF II Collaboration], *Phys. Rev. Lett.* **93** (2004) 072001; V. M. Abazov *et al.* [D0 Collaboration], *Phys. Rev. Lett.* **93** (2004) 162002.
- 15) A. Abulencia *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **96** (2006) 102002.
- 16) K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0505037; B. Aubert *et al.* [BABAR Collaboration], *Phys. Rev. D* **74** (2006) 071101.
- 17) K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0505038; A. Abulencia *et al.* [CDF Collaboration], arXiv:hep-ex/0612053.
- 18) G. Gokhroo *et al.*, *Phys. Rev. Lett.* **97** (2006) 162002, and A. E. Bondar, these Proceedings. The signal has been confirmed by BaBar Collaboration, see P. Grenier, talk at Moriond QCD 2007.
- 19) K. Abe *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **94** (2005) 182002.
- 20) M. B. Voloshin and L. B. Okun, *JETP Lett.* **23** (1976) 333.
- 21) F. E. Close and P. R. Page, *Phys. Lett. B* **578** (2004) 119; M. B. Voloshin, *Phys. Lett. B* **579** (2004) 316; N. A. Tornqvist, *Phys. Lett. B* **590** (2004) 209. C. Y. Wong, *Phys. Rev. C* **69** (2004) 055202; E. Braaten and M. Kusunoki, *Phys. Rev. D* **69** (2004) 074005; E. S. Swanson, *Phys. Lett. B* **588** (2004) 189 and **598** (2004) 197; M. T. AlFiky, F. Gabbiani and A. A. Petrov, *Phys. Lett. B* **640** (2006) 238; E. Braaten, M. Lu and J. Lee, arXiv:hep-ph/0702128; S. Fleming, M. Kusunoki, T. Mehen and U. van Kolck, arXiv:hep-ph/0703168.
- 22) M. B. Voloshin, *Int. J. Mod. Phys. A* **21** (2006) 1239.
- 23) T. Barnes and S. Godfrey, *Phys. Rev. D* **69** (2004) 054008; T. Barnes, S. Godfrey and E. S. Swanson, *Phys. Rev. D* **72** (2005) 054026; E. J. Eichten, K. Lane and C. Quigg, *Phys. Rev. D* **69** (2004) 094019, *Phys. Rev. D* **73** (2006) 014014 [*D* **73** (2006) 079903 (E)]; C. Meng and K. T. Chao, arXiv:hep-ph/0703205.
- 24) M. Suzuki, *Phys. Rev. D* **72** (2005) 114013.
- 25) B. Aubert *et al.* [BABAR Collaboration], *Phys. Rev. D* **73** (2006) 011101.
- 26) The interpretation of $X(3872)$ as a state of dynamical origin has been proposed, see C. Hanhart, Yu. S. Kalashnikova, A. E. Kudryavtsev and A. V. Nefediev, arXiv:0704.0605 [hep-ph], together with the references therein and the discussion in M. B. Voloshin, arXiv:0704.3029 [hep-ph].
- 27) P. Colangelo, F. De Fazio and S. Nicotri, arXiv:hep-ph/0701052, to appear on PLB.
- 28) R. Casalbuoni *et al.*, *Phys. Rept.* **281** (1997) 145; P. Colangelo, F. De Fazio and T. N. Pham, *Phys. Rev. D* **69** (2004) 054023.